Journal of Arid Environments 73 (2009) 280–286

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Compensating for diminishing natural water: Predicting the impacts of water development on summer habitat of desert bighorn sheep

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ARTICLE INFO

Article history:
Received 3 July 2008
Received in revised form
23 September 2008
Accepted 29 September 2008
Available online 22 November 2008

Keywords:
Desert bighorn sheep
Guzzlers
Historic habitat
Mojave desert
Ovis canadensis nelsoni
Summer habitat
Water development

ABSTRACT

Artificial water sources have been used for decades to enhance and restore wildlife habitat but the benefits of their use have been subject to debate. During the past century, the number of natural springs in Joshua Tree National Park, California, USA, has declined. In response to concerns about the viability of the bighorn sheep (*Ovis canadensis nelsoni*) population, a number of water developments were constructed throughout the park. We modeled potential historical and present-day summer habitat of female bighorn sheep to evaluate the effectiveness of the artificial and remaining natural water sources in maintaining habitat and to determine how loss of artificial sources might affect future habitat availability. Prior to 1950, 583.5 km^2 of summer habitat was potentially available. Presently, only 170.6 km^2 of habitat is available around natural water sources and 153.5 km^2 is available around guzzlers. When all perennial water sources are included in the habitat model (minus overlap), 302.3 km^2 of summer habitat is potentially available. This represents only 51.7% of summer habitat available prior to 1950. Without artificial water developments, 47.7% of present-day summer habitat would be lost, which raises important management questions regarding the debate about what is natural or artificial within otherwise protected areas.

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1. Introduction

Artificial water sources have been used for decades to enhance or restore wildlife habitat in arid regions based on the assumption that the net effects of water development were positive (Rosenstock et al., 1999; Krausman et al., 2006). Although, the benefit of providing artificial water sources for wildlife is now a subject of considerable debate, many investigators continue to assert that water developments increase population carrying capacity, allow for range expansions, and mitigate loss of habitat and loss of naturally occurring water (Bleich et al., 1982; Rautenstrauch and Krausman, 1989; deVos and Clarkson, 1990; Kie et al., 1994; Dolan, 2006). In contrast, others cite instances of no response by wildlife to new water sources (Krausman and Etchberger, 1995), or describe potential negative impacts such as changes in natural movement patterns, displaced native ungulates or increased mortality due to poor water quality or increased predation (Broyles, 1995; Broyles and Cutler, 1999). In addition, the use and maintenance of water developments on sensitive lands are controversial because wildlife populations may be artificially maintained on lands managed as wilderness areas (Czech and Krausman, 1999; Bleich, 2005).

Desert bighorn sheep are medium-sized ungulates that occupy mountain ranges in arid regions of southwestern North America (Bleich et al., 1996). Populations are particularly vulnerable to detrimental changes in habitat availability due to low female dispersal rates and the long distances between populations (Epps et al., 2004; Epps et al., 2007). In recent years, a transition to more arid climatic conditions has been documented in the southwest, resulting in less precipitation (Seager et al., 2007) and shifts in timing of precipitation (Weltzin et al., 2003), which may lower the reproductive success of bighorn sheep (Douglas and Leslie, 1986; Wehausen et al., 1987) and may increase the probability of population extirpation (Epps et al., 2004).

During summer months, water sources are considered as an essential component of suitable habitat for nearly all desert bighorn sheep populations (Bleich et al., 1997; Andrews et al., 1999; Turner et al., 2004; Oehler et al., 2005; Sappington et al., 2007; but, see Warrick and Krausman, 1989) and the presence of dependable water sources has been strongly correlated with population persistence (Epps et al., 2004). Artificial water sources have been used for decades to enhance and restore habitat for desert bighorn sheep (Halloran and Deming, 1958; Weaver et al., 1958; Werner, 1984), but the benefits are not always obvious. Most authors agree

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0140-1963/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.jaridenv.2008.09.021

that artificial water sources support or increase some, but not all, desert bighorn populations (Rosenstock et al., 1999). The predicted transition to a more arid climate and resultant impacts to desert bighorn sheep populations indicate that the use of water developments may be an important conservation tool to maintain available habitat, particularly in instances where loss of available water has been exacerbated by anthropogenic activities.

The availability of perennial water for bighorn sheep has been a concern for resource managers in Joshua Tree National Park (JOTR), located in an arid region of California, USA. The number of perennial water sources has declined since the mid-1950s because of a combination of increased aridity and increased pumping of ground water (Douglas and White, 1979). For example, water flow at Stubbe Spring, a primary water source for bighorn sheep within the park, decreased from 222 gallons per day in 1948, to 96 gallons per day in 1964, and was flowing only intermittently in 1968 (Douglas and White, 1979). In response to concerns about the viability of the bighorn sheep population, 12 guzzlers were constructed throughout the park (Douglas, 1975). These projects were considered to be only partially successful because several received little or no use by bighorn sheep (Douglas and White, 1979). Of the six developments installed between 1968 and 1978, only two were being used by bighorn sheep in 1979 (Douglas and White, 1979).

The number of natural water sources at JOTR has continued to decline in recent years. Ten natural perennial water sources were located in bighorn sheep habitat in 1979 (Douglas and White, 1979) but only five of those water sources remain. Although many of the original artificial water developments are no longer operational, five continue to supply water to bighorn sheep. To evaluate the effectiveness of artificial water developments in maintaining habitat for female bighorn sheep and to evaluate how loss of the artificial water sources might affect movement patterns and future habitat availability, we modeled seasonal habitat use of female bighorn sheep in the Wonderland of Rocks and Queen Mountain regions of the park. Using the predictive model, we then determined present-day summer habitat and probable availability of historical summer habitat in Joshua Tree National Park prior to the decline of natural water sources and initiation of water development projects. We quantify the effects of the loss of water sources on habitat availability and evaluate the potential long-term impacts on summer habitat if water developments were to be removed or not maintained.

2. Materials and methods

2.1. Study area

The study was located in JOTR, California (34°N, 116°E). Elevation is between 680 m and 1775 m and topography generally is steep and rocky with large granite boulders covering some areas. Dominant vegetation is strongly associated with elevation, and consists of *Larrea tridentata–Ambrosia dumosa* associations at lower (<1000 m) elevations; *Yucca schidigera*, *Yucca brevifolia*, and *Coleogyne ramosissima* associations at the mid-elevations (900–1400 m); and *Juniperus californica* associations at the higher (>1100 m) elevations (Leary, 1977). The climate is seasonal, summer temperatures can be >44 °C and winter low temperatures can be <−2 °C. Average rainfall is <10.0 cm per year, with most occurring during winter and summer months.

2.2. Bighorn sheep captures

On 29–30 October 2002, ten adult female desert bighorn sheep were captured within the Wonderland of Rocks and Queen Mountain region of the park and fitted with ARGOS satellite uplink capability collars (TGW-3580 store-on-board units, Telonics Inc., Mesa AZ). Collars incorporated an automatic breakaway release and mortality sensor. Within the Wonderland of Rocks/Queen Mountain region, population size was estimated as 54 bighorn sheep (95% C.I. 39–68) in 2003 and 59 bighorn sheep (95% CI 28–89) in 2004 (Thompson et al., 2007). Assuming females comprised 50% of the population, the 10 collared animals represented approximately one third of the females in the population. Three locations daily (at 0500, 1200, and 2000 h) per animal were obtained from June through September of 2003 and 2004. Over 4700 collar-generated location points were collected. Erroneous location points resulting from satellite signal malfunctions (<0.5% of total) were removed. All location outliers (possible errors) were checked for accuracy by confirming that previous and subsequent locations were within reasonable (approx. 1.0 km) proximity to the outlier; any outliers that remained suspect were removed. All collars retrieved from the field were found within 10 m of the last GPS coordinates reported via satellite.

2.3. Modeling female bighorn sheep critical summer habitat

Habitat of adult female bighorn sheep was determined by measuring slope (percent converted to a proportional scale from 0 to 1), distance to dependable water (km), and ruggedness (Vector Ruggedness Measure with range 0–1; Sappington et al., 2007) at satellite recorded locations collected June through September. These variables are known to be good predictors of bighorn sheep occurrence, and have been successfully used to model habitat (Holl, 1982; Zeigenfuss et al., 2000; Sappington et al., 2007). All habitat variable measurements of bighorn sheep and random locations were determined using GIS (ArcView 3.2 and ArcMap 9.1; ESRI, Redlands, CA). The Vector Ruggedness Measure was calculated using an ArcView script that first calculated the angles of a three-dimensional vector normal to each 30 × 30 m cell in a grid covering the study area and then, for each cell, quantified the dispersion of vectors or variation in terrain angles and aspect across a 3 × 3 moving window (grid of 9 cells centered on the focal cell) (Sappington et al., 2007).

A binary logistic regression analysis, using 976 randomly selected ewe locations and 976 random points as dependent variables, was used to determine if habitat attributes were predictive of ewe locations (Manly et al., 2002). Although application of logistic regression to use-availability data, for which the sampling fraction of used sites is unknown, produces resource selection function values (RFS) that are simply proportional to the probability of animal occurrence (Manly et al., 2002; Keating and Cherry, 2004), this type of analysis has been shown to yield robust and valid estimates of habitat selection (Boyce and McDonald, 1999; Johnson et al., 2006). The Hawth's tools© extension within ArcMap to generate random points within the study area and spatially enforced a minimum distance of 10 m between points. We further constrained random points to areas of slope greater than 20% (Etchberger et al., 1989; Bangs et al., 2005), since comparing ewe locations to areas of unlikely occurrence (i.e. flat areas) is of little value. We only used locations recorded at 0500 and 1200 h for analysis because sheep often did not travel during nighttime hours (unpublished data) and many of the locations at 2000 were similar to those at 0500.

Model chi-square tests of the likelihood ratio and Wald statistics were used to assess overall model fit and the strength of individual variable contributions to the model was evaluated using the Baysian information criterion (BIC), calculated as the difference between the Wald chi-square of a logistic coefficient and the natural logarithm of the sample size (Raftery, 1995; Pampel, 2000). If the BIC of a regression coefficient exceeds 10, the independent variable can be interpreted as a very strong predictor of the dependent variable (Raftery, 1995). We entered the logistic regression equation into the GIS raster calculator to generate approximations of RSF values and placed these values in 20 percentiles to create a rank of habitat suitability for mapping summer habitat of ewes across the park (Boyce and McDonald, 1999; Keating and Cherry, 2004). The areas defined by the percentile(s) of RSF values that incorporated ≥85% of bighorn sheep locations were interpreted as critical summer habitat.

2.4. Establishing water sources and measuring historical and present-day critical habitat availability

We determined locations of historical, dependable water sources within the park by researching historical mining claims, legal documents, county records, geological survey records and other official documents in the JOTR library archives. We then determined locations of extant dependable water sources within the park from current maps, park staff, and personal observations and separated extant dependable water sources into natural and artificial categories, and subdivided artificial features into guzzlers and dams.

Only historic water sources documented as having flowing surface water during summer months were considered dependable (Table 2). Although springs and seeps in the same area may have different hydrological causes and their flow locations and amounts may vary spatially and temporally (Maxey, 1968), there is no study of the JOTR regional hydrology that we can use to identify springs that are continuously supplied by regional groundwater systems. If some of the historic springs were supplied by local groundwater sources and were dependent on nearby seasonal rainfall, observations of surface flow only in years with heavy rainfall would not be indicative of dependable surface water. We examined rainfall data from 1936 to 1970 (9.98 cm, mean; ±6.01 SD) for the town of Twentynine Palms (adjacent to JOTR) to assess whether observed flow rates of historical springs in JOTR coincided with periods of high precipitation. No such pattern was apparent in our data; there were no recorded observations of spring flow in the two years with highest rainfall (1941, 20.98 cm and 1943, 28.45 cm), whereas, four springs were reported flowing during summer months in two of the years with the lowest precipitation (1942, 2.40 cm and 1948, 3.60 cm).

We determined total areas of historical and present-day critical summer habitat from the GIS-based models, and then calculated potential loss of critical habitat that would occur if water developments were removed or became inoperable. We eliminated artificial dams from the calculation of potential habitat loss because water pools behind dams were ephemeral during dry summers (C. Lowrey, unpublished data).

3. Results

Logistic regression analysis indicated a strong ability to differentiate between bighorn sheep summer locations and random points using the habitat variables described (overall model: $\chi^2 = 788.5$, df = 3, $P < 0.0001$, Nagelkerke $R^2 = 0.443$). BIC values for distance to water, slope, and ruggedness were 268.2, 117.2 and 40.6 respectively. The BIC values indicate that all three habitat variables are very strong predictors of sheep locations and that distance to dependable water is the most important variable explaining ewe summer locations within the study area (Table 1). The odds ratio (exponential of the logistic regression coefficient) of distance to water indicates that the probability of sheep occurrence is reduced by a factor of 0.64 for every 1 km increase in distance to dependable water. As of 2004, there were two naturally occurring perennial water sources and two functioning guzzlers and/or artificial dams within the Wonderland of Rocks/Queen Mountain study area. Mean distance of ewes from a dependable water source was 2.4 km (SE = 0.51 km).

Table 1
Maximum likelihood estimates (MLE) of regression coefficients for the three habitat variables, 95% confidence intervals (CI), Wald chi-square (χ^2) and P values derived from logistic regression analyses of summer bighorn ewe locations verses random available locations in Joshua Tree National Park, California.

Habitat variable	MLE	CI	Wald χ^2	df	P
Distance to water	−0.45	−0.51 to −0.40	275.8	1	<0.0001
Ruggedness	35.79	25.89 to 46.10	48.2	1	<0.0001
Slope	3.51	0.029 to 0.041	124.8	1	<0.0001

Based on our examination of the archives, we found evidence for a minimum of 19 previously existing dependable (see Section 2) natural springs within JOTR (Table 2). When incorporating these water sources in habitat models for the entire park, we found that prior to 1950, 583.5 km^2 of critical summer habitat was potentially available for adult female desert bighorn sheep (Fig. 1). As of 2004, there were only five naturally occurring perennial water sources and eight functioning (perennial) guzzlers or artificial (ephemeral) dams within the park (Table 3). GIS-based models indicated 170.6 km^2 of critical summer habitat currently available based on proximity to natural water sources. Perennial water developments provided an additional 153.5 km^2 of critical habitat (Fig. 2). When all perennial water sources are included in the habitat model (minus overlap), 302.1 km^2 of critical summer habitat is potentially available for female bighorn sheep in JOTR. Thus, current habitat near natural springs represents 29.2% of historical critical summer habitat and current habitat near water developments represents 26.3% of historical habitat in terms of total area. Current habitat around all perennial waters represents only 51.7% of critical summer habitat available to bighorn sheep prior to 1950. If water developments were removed or not maintained, 47.4% of present-day summer habitat would be lost. Maintenance of guzzlers is particularly important because during dry years, guzzlers can go dry, and cause a further decrease in availability of habitat. In addition to the loss of critical habitat, the drying of Pinkham Spring (c 1968) in the center of the park increased isolation of bighorn summer habitat in the eastern and western portions from a maximum distance of 17.3 km separating water sources before 1968, to 25.7 km separating current water sources.

4. Discussion

Water is the most important variable in logistic regression models defining female bighorn sheep habitat during summer months in Joshua Tree N.P., a result that is consistent with studies of habitat selection in other populations. Virtually every habitat model developed for desert bighorn sheep has identified water as an important correlate of sheep use (McCarty and Bailey, 1994; Bleich et al., 1997; Andrews et al., 1999; Turner et al., 2004; Oehler et al., 2005; Sappington et al., 2007). Further, an analysis of 20th Century extinction patterns of desert bighorn sheep populations in California found the existence of predictable surface water, in addition to elevation and maximum precipitation, to be strongly correlated with population persistence (Epps et al., 2004). In our study, ninety percent of all bighorn ewe locations were less than 3.5 km from a natural or artificial water source and mean distance of ewe locations from water was 2.4 km.

Based on predictions from our habitat models, the loss of 19 natural perennial water sources in JOTR during the latter half of the twentieth century has greatly decreased the amount of summer

Table 2
Historical water sources, now dry, that were potentially available to bighorn sheep in Joshua Tree National Park, California, USA, prior to 1950.

Water source	Easting	Northing	Bighorn use	Documented water flow	Year documented dry
Bare Tree	550310	3760550		1948[e]	1968[e]
Black rock Springs	555120	3765680		1942[e]	1955[e]
Buckhorn Spring	627327	3731892		1940[e]	1945[e]
Canejo Spring	615126	3735320		1945[e]	Unknown
Chuchwalla Bill	550120	3765100		1948[e]	1968[e]
Covington Spring	565320[a]	3765000[a]		1944[e]	1961[e]
Coyote Hole	560800	3770950		1948[e]	1968[e]
Eagle Spring	630645[a]	3751103[a]		1948[e]	Unknown
Hayfield Spring	629900	3732700	1920[e]	1900[c]	1955[e]
Leather Leaf Spring	578150[a]	3769400[a]		1920[c]	Unknown
Midway	616350[a]	3731300[a]	1960[e]	1960[e]	Unknown
Munsen Canyon	616200	3730620	1965[e]	1901[c]	1968[b]
Pigeon Spring	567000[a]	3765000[a]		1944[e]	1964[e]
Pine Spring	586634	3767419	1938[d]	1938[d]	1957[f]
Pinion Spring	580650	3750300		1946[e]	Unknown
Pinkham Spring	605400	3745450		1923[e]	1968[e]
Quail Springs	568600	3766350	1968[e]	1945[f]	1957[f]
Rattlesnake	550185	3769708	1966[e]	1948[e]	1970[b]
Willow Hole	578450	3769900		1915[g]	1970[e]

[a] Approximate location.
[b] Ephemeral.
[c] Riverside County, California record of water diversion, 1900.
[d] Joshua National Park Archive file #N3043.
[e] Joshua Tree National Park Water Source Report files.
[f] R.P. Broyles. Joshua Tree National Park Future Guzzler Memorandum, 1968.
[g] San Bernardino County, California record of water diversion, 1915.

habitat available for desert bighorn sheep. Artificial water developments in the park were initially considered to be only partially successful (Douglas and White, 1979), possibly because it can take time for ungulate populations to discover and use new resources, particularly point sources (Krausman and Etchberger, 1995). However, artificial water sources now represent half of the existing perennial water sources available to desert bighorn sheep. Rather than artificially elevating population densities of bighorn sheep, our observations indicate that existing artificial water developments have partially compensated for the loss of natural water sources in JOTR by maintaining 47.4% of current critical summer habitat available to ewes. Nevertheless, currently available critical summer habitat is only 51.7% of that estimated for historical critical summer habitat within the park. In the absence of anthropogenic water sources, only 29.2% of historical habitat would be available.

Whether artificial water sources are ecologically similar to natural water or alter movement patterns of native wildlife

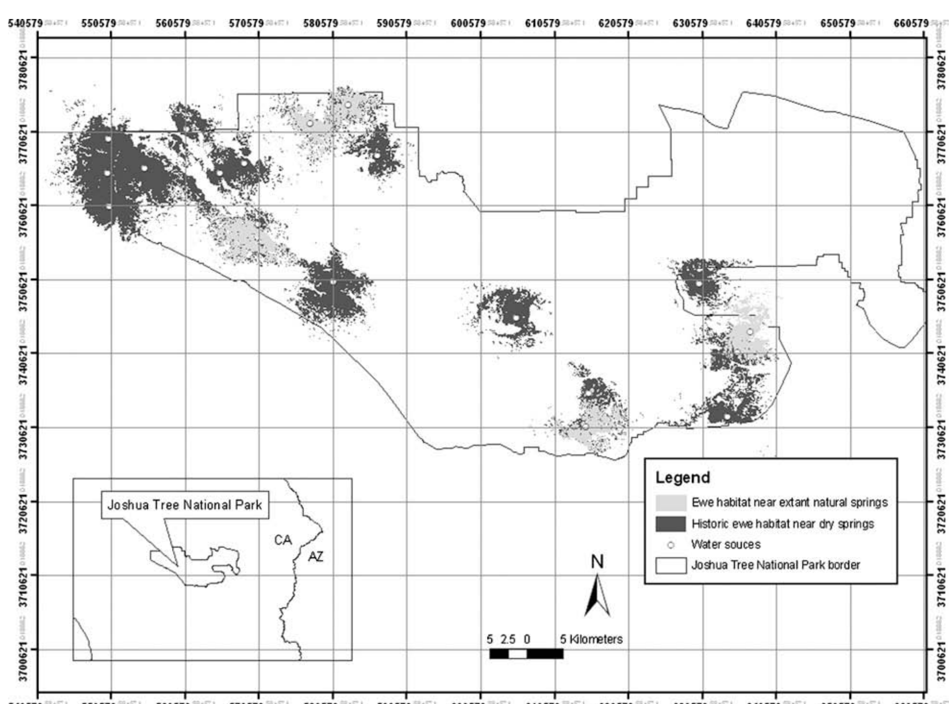

Fig. 1. Joshua Tree National Park, California, USA, showing modeled potential critical summer bighorn sheep habitat surrounding historical (prior to 1950) dependable water sources. Source: Joshua Tree National Park Archives.

Table 3
Known water sources potentially available to bighorn sheep in Joshua Tree National Park, California, USA, as of 2004. Coordinates are in UTM. Water pools behind dams were often dry during summers. Documented sheep use is based on information from Joshua Tree N.P. archives, early reports and personal observation.

Water source	Type	Easting	Northing	Year built	Documented use by bighorn sheep
49 Palms Oasis	Natural spring	582560	3774290		1945[c]
Johnson Spring	Natural spring	577456	3771799		1938[c]
Lost Palms Oasis	Natural spring	614712	3730825		1964[a]
Stubbe Spring	Natural spring	570482	3758218		1968[d]
Buzzard Spring	Natural spring	636897	3743665		1957[c]
Pine City	Guzzler	586634	3767419	1970	1938[b]
Russis Rocks	Guzzler	657120	3746201	1982	2007[e]
Rattlesnake	Guzzler	550185	3769708	1968	1968[d]
Pinyon Wells	Guzzler	582800	3750300	1978	1986[a]
Barker Dam	Dam	578878	3765882	1920[c]	2001[e]
Cow Camp Dam	Dam	577385	3766642	1920[c]	2001[e]
Keys Ranch Dam	Dam	577000	3767637	1920[c]	2001[e]
Coxcomb Adit Dam	Dam	648014	3767747	1971	1979[e]

[a] Joshua Tree National Park Guzzler Report and Inventory. J. Ashdown, 2002.
[b] Joshua National Park Archive file #N3043.
[c] Joshua Tree National Park Water Source Report files.
[d] Douglas and White, 1979.
[e] Mike Vamstead, National Park Service, Pers. comm.

populations depends, in part, on the location of water developments (Douglas and White, 1979; Burkett and Thompson, 1994; Rosenstock et al., 1999; Krausman et al., 2006). Artificial water sources in JOTR are located in terrain that is similar in slope and ruggedness to terrain surrounding natural springs used by bighorn sheep. Indeed, several artificial water sources are close to natural water sources that are now dry. Thus, rather than altering historic movement patterns of bighorn ewes, it is likely that artificial water sources in JOTR preserve routes for movement that otherwise might be disrupted by the drying of natural springs.

For species such as bighorn sheep, the conservation of individual populations also is important for the maintenance of connectivity within a metapopulation structure and for genetic diversity (Bleich et al., 1996; Epps et al., 2005). Because species that persist in small, fragmented populations may experience an accelerated loss of genetic diversity (Epps et al., 2005) and are particularly susceptible to the effects of stochastic events (Lande, 1988), it is important to prevent the spatial isolation of habitats. Thus, loss of summer habitat in the absence of artificial water sources in JOTR could impact persistence of bighorn sheep on larger spatial scales.

Historical mining and other forms of development, in addition to changes in climate, have drastically reduced water availability for desert bighorn in the southwest (Graf, 1981). Agencies responsible for bighorn sheep and their habitat as well as private conservation groups have spent significant resources providing artificial water sources as part of management plans (Bleich et al., 1982; Werner, 1984; Rosenstock et al., 1999). Although concerns

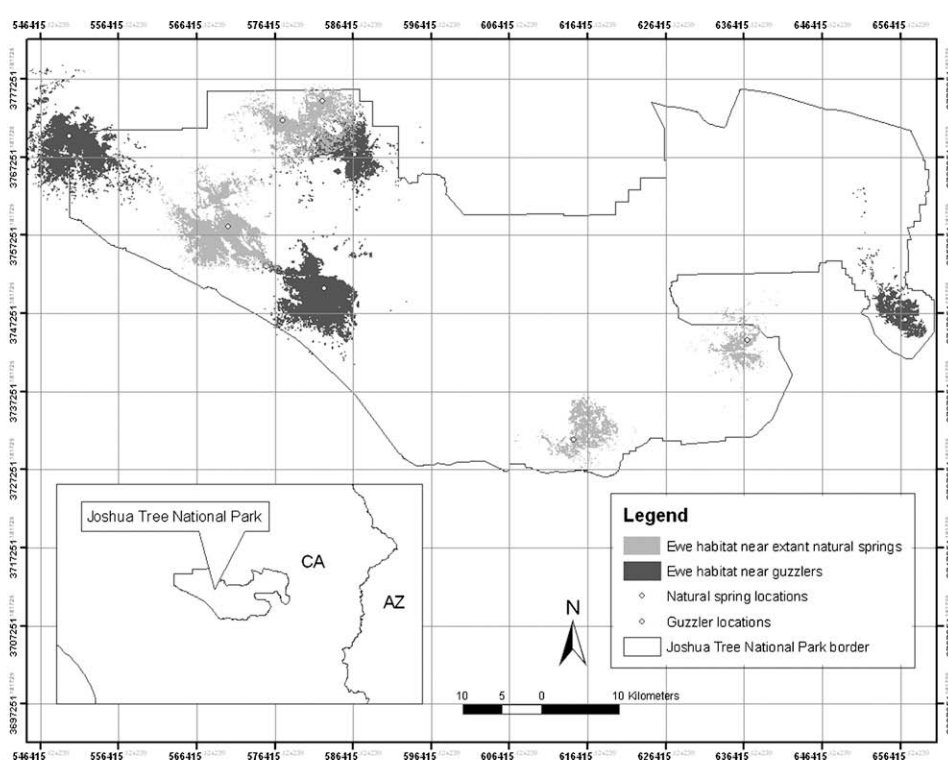

Fig. 2. Joshua Tree National Park, California, USA, showing modeled critical summer bighorn sheep habitat surrounding existing water sources during 2002–2003.

about water developments often center on the negative consequences of maintaining artificially high animal populations in sensitive areas such as national parks, our results reveal that these water developments may be maintaining populations in the face of historical habitat loss that, to some extent, is due to anthropogenic causes. The magnitude of change in distribution of desert bighorn sheep habitat that would result from elimination of artificial water sources in JOTR raises concerns about whether the bighorn sheep population would persist on natural water alone and underscores the importance of modeling the effects of water management decisions in other wildlife populations, particularly if the predicted transition to a more arid environment continues in the southwest.

Construction or maintenance of water developments for the benefit of ungulates remains a controversial issue (Krausman et al., 2006). However, resource managers and conservation biologists must decide how to maintain population size, habitats, and connectivity for the future, especially when considering issues such as regional and global climate changes. Water developments may be an important conservation tool to maintain critical habitat, particularly in instances where loss of available water has been exacerbated by anthropogenic activities. Our research demonstrates the importance of artificial water sources for maintaining historical and present-day critical summer habitat for bighorn sheep in JOTR and provides a method to assess the degree to which artificial water sources can compensate for the loss of natural water due to anthropogenic disturbance and climate change.

Acknowledgements

Funding for this project was provided by the National Resources Preservation Program of the U.S. Geological Survey and the National Park Service. We thank the Natural Resource staff at Joshua Tree National Park, California, and the California Department of Fish and Game, who conducted the capture operation. We thank J. Jaeger and Vern Bleich for their valuable comments on an earlier version of the manuscript, and Tom Hurst for discussions about hydrology of the region. Animal use protocols were approved by Animal Care and Use Committees for the University of Nevada, Las Vegas and the U.S. Geological Survey. The use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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